The Heating of the ICM: Energy Crisis and viable solutions

Paolo Tozzi

Oss. Astronomico di Trieste, via G.B. Tiepolo 11, 34100 Trieste – Italy

Abstract. X–ray observations indicate that non–gravitational processes play a key role in the thermodynamics of the Intra Cluster Medium (ICM). The effect of non–gravitational processes is imprinted in the ICM as an entropy minimum, whose effects are visible in the Luminosity–Temperature relation and in the Entropy–Temperature relation. However, the X–ray emission alone cannot discriminate between different mechanisms and sources of heating. There are no answers at present to the following questions: how much non–gravitational energy per baryons is present in the ICM? When was this energy injected? Which are the sources of heating? The embarrassment in front of these questions is amplified by the fact that the most viable sources of heating, SNae and stellar winds, seem to be inefficient in bringing the ICM to the observed entropy level. We may call it the *energy crisis*. Here we review the main aspects of this crisis, listing possible solutions, including other sources, like AGNs and Radio Galaxies, or other mechanisms, like large scale shocks and selective cooling.

1. Evidences for non–gravitational heating

Observations in the X–ray band provided convincing evidences for non–gravitational heating of the diffuse baryons in the potential wells of groups and clusters of galaxies (ICM). Among them: the shape of the L–T relation (steeper than the self–similar behaviour $L \propto T^2$ predicted in the case of gravitational processes only) and the entropy excess in the center of groups, recently found by Ponman, Cannon & Navarro (1999). Non–gravitational heating of the ICM is expected also on the basis of observations of an average metallicity $Z \simeq 0.3 \ Z_\odot$. In fact, SNae and stellar winds are the most viable source of heating and metal enrichment of the ICM. It should be understood how much of the ejected energy goes into the ICM and if it is enough to generate the observed entropy plateau.

2. How the entropy works

If the excess entropy is present in the baryons before collapse (*external heating*, or preheating, see Tozzi & Norman 2001, hereafter TN), it will be preserved in the cores of dark matter halos after virialization. In virtue of the extra pressure support, in fact, the gas is accreted adiabatically without shock heating. The excess entropy also decreases the density in the central regions. This, in turn,
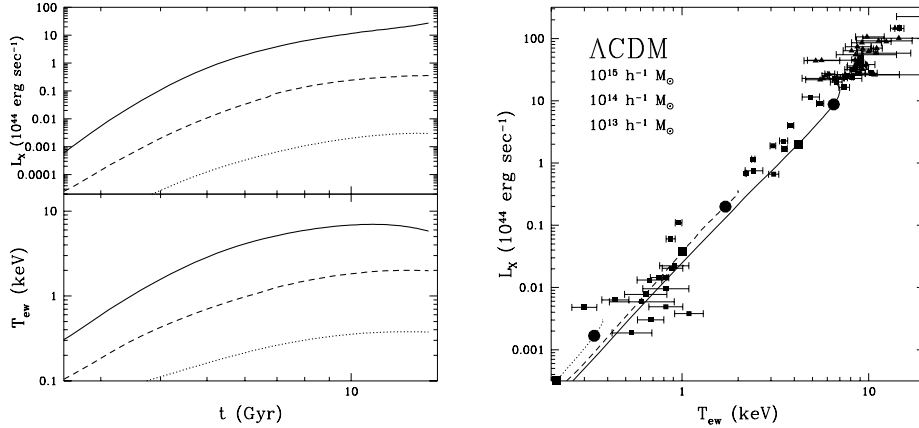
Figure 1.   Left: The evolution of the bolometric luminosity L_X and of the emission–weighted temperature T_{ew} is shown as a function of time for a final mass of $10^{15} - 10^{14} - 10^{13} h^{-1} M_\odot$ (solid, dashed and dotted lines respectively) for a ΛCDM cosmology, with an initial adiabat $K_{34} = 0.3$ (in units of 10^{34} erg cm^2 g$^{-5/3}$). Right: The evolutionary tracks along the L–T relation for the halos on the left. Large squares and circles mark $z = 1$ and 0.5 respectively. Local data from Allen & Fabian (1998), Arnaud & Evrard (1999), Ponman et al. (1996).

rapidly decreases the X–ray luminosity which is proportional to the square of the density. The effect is stronger in small groups, where the energy responsible for the entropy is comparable to the gravitational one, while clusters, where gravity is dominant, are mostly unaffected. This produces a steepening of the L–T relation and breaks the scale invariance in the density profiles of clusters and groups. The entropy has also the effect of suppressing the radiative cooling in the central regions. This model allows to trace the evolution of X–ray luminosity and temperature of groups and clusters after assuming a Press & Schechter–like law for the accretion rate of baryons (see TN). In Figure 1 we show that the evolution corresponds to tracks moving along the local L–T relation. Thus, a constant L–T is predicted up to $z \simeq 1$, in agreement with observations (Mushotzky & Scharf 1997, Borgani et al. 2001). The external entropy level that satisfies the observations is in the range $K_* = 0.2 - 0.3 \times 10^{34}$ erg cm^2 g$^{-5/3}$ (see TN).

3.   The energy crisis

The external heating scenario is appealing, but the excess entropy cannot be spread uniformly into the cosmic baryons at high redshifts, because this would make the Ly$_\alpha$ forest to disappear. Recently, it has been estimated that the level of preheating in the Ly$_\alpha$ clouds is of the order of few $10^4 K$ (Cen & Brian 2001), corresponding to an entropy level at least one order of magnitude lower than that observed in groups. A possible solution is that only the baryons that end up in the cores of groups and clusters are heated by a biased distribution of
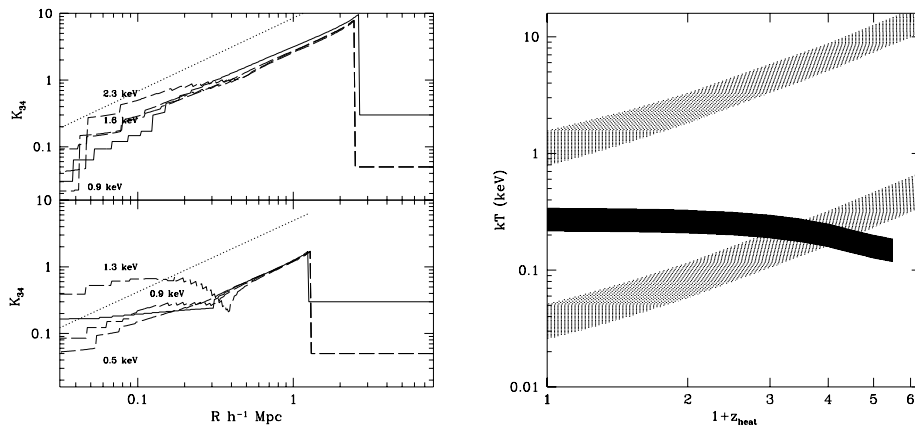
Figure 2.   Right: The entropy profiles in the external (solid) and the internal (dashed lines) scenario for a rich ($M = 10^{15}h^{-1}M_\odot$, top) and a small cluster ($M = 10^{14}h^{-1}M_\odot$, bottom). The external entropy level is $K_{34} = 0.3$. In the internal scenario, a total energy of 1–2 keV per particle is released, as shown by the labels. Left: The upper and lower stripes show the required energy per particle needed to obtain an excess entropy of $K_{34} = 0.2 - 0.3$ in virialized structures and in the background baryons respectively. The solid stripe is the energy per particle dumped in the ICM by TypeII and TypeIa SNae after Pipino et al. (2001).

sources. Such a warm, low density gas would be unobservable at high z, and can be detected as OVI absorption systems at low (Tripp, Savage & Jenkins 2001) or at intermediate z (Reimers et al. 2001).

If OVI systems cannot account for the pre–heated baryons, the ICM must be heated after the collapse. Of course, for a given entropy level, the much higher density of the collapsed regions implies a much higher energy input. An energy budget of 1–2 keV per particle (3–10 times higher than that in the external scenario) seems to be required to reproduce the entropy floor (see also Wu, Fabian & Nulsen 1999, Valageas & Silk 1999) and entropy profiles similar to the ones predicted in the external heating scenario (see Figure 2, left).

Despite the SNae can provide a large amount of energy, their efficiency in heating the gas is unknown. In particular, if the heated gas has high density, the thermal energy received from SNae is rapidly radiated away, with a small net increase in the gas entropy. A recent study has been made by Pipino et al. (2001), starting from the observed luminosity function of cluster galaxies. The efficiency of TypeII and TypeIa SNae is computed assuming a spherical gas distribution around galaxies. The energy per particle dumped in the ICM as a function of redshift is plotted in Figure 2 (right, black stripe). It turns out that SNae can contribute a substantial amount of the required energy ($\simeq 0.3$ keV/particle), which is, however, lower than that needed in virialized region (upper stripe). The first attempts to include the stellar feedback in hydrodynamical simulations, seem to indicate a low efficiency from SNae (see, e.g., Borgani et al.
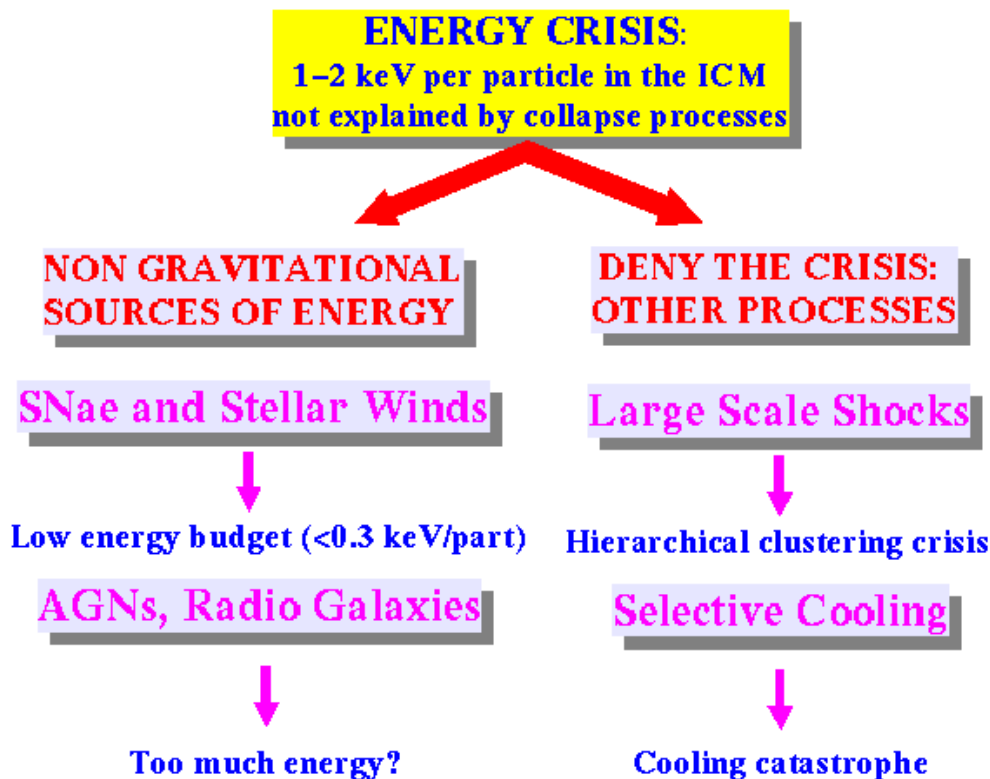
Figure 3.   A sketch of the current situation. The description may be not exhaustive.

2001). Following the natural predisposition of cosmologists towards the use of the word *crisis*, I would call this empasse the *energy crisis* of the cosmic baryons.

4.   Solutions and possible way out

If SNae will be shown unadequate for this job, the energy crisis can be solved by other sources of non–gravitational energy. Several studies already considered AGNs as the main source of heating. Radio Galaxies can provide an energy output two orders of magnitude larger than stellar sources, and they can heat the baryons at large distance, reaching low densities for which the radiative cooling is negligible (see Inoue & Sasaki 2001). On the other hand, AGNs can heat the baryons so efficiently as to exceed the upper limit of the comptonization parameter of the CMB (Yamada & Fujita 2001).

As in political life, a possible way to solve the crisis is to deny it: some viable scenario avoids the intervention of non–gravitational heating to generate the entropy plateau. The extra energy could be due to gravitational shocks produced by large scale structure (filaments and sheets) before the collapse of group–sized regions. However, this requires large scale shocks to occur at redshifts much larger than the typical formation epoch of the cores of clusters or groups, which can be as high as $z \simeq 3$ in ΛCDM universes. These large–scale effects have never

been noticed in N–body simulations with current CDM power spectra, for which there is a large consensus.

Another way consists in simply eliminating the low entropy gas. Some simulations suggest that the cooling itself, mostly efficient in the higher density region, can reproduce the X–ray properties of clusters, like the L–T relation (Muanwong et al. 2001). In this case, the entropy plateau is created by the removal of the lowest entropy gas, which cools out of the diffuse, emitting phase. However, the majority of present–day simulations, in absence of any feedback, find an unacceptably high fraction of cooled baryons (Balogh et al. 2001). We must stress that the cooling is extremely difficult to treat numerically and there is consensus among simulations only at very high resolutions.

To summarize, denying the crisis can lead to a worst crisis, like the inversion of the clustering hierarchy or the cooling catastrophe, as sketched in Figure 3. At the present stage there are no obvious solutions and it is important to investigate all the possible way out. Both X–ray observations and theoretical modelling will be crucial in the next years to get out of this empasse.

References

Allen, S.W., & Fabian, A.C. 1998, MNRAS, 297, 63L

Arnaud, M., & Evrard, A.E. 1999, MNRAS, 305, 631

Balogh, M., Pearce, F., Bower R., Kay S. 2001, MNRAS, 326, 1228

Borgani, S. et al. 2001, ApJ in press, astro-ph/0108329

Cen, & Bryan 2001, ApJ, 546, 81L

Inoue, S., & Sasaki S. 2001, ApJ in press, astro-ph/0106187

Muanwong et al. 2001, ApJL, 552, L27

Mushotzky, R. F., & Scharf, C. A. 1997, ApJ, 482, 13

Ponman, T. J., et al. 1996, MNRAS, 283, 690

Ponman, T. J., Cannon, D. B., & Navarro, F.J. 1999, Nature, 397, 135

Reimers, D., et al. 2001, A&A submitted, astro-ph/0106097

Tozzi, P., & Norman, C. 2001, ApJ, 546, 63 (TN)

Tozzi, P., Scharf, C., & Norman, C. 2000, ApJ, 542, 106 (TSN)

Tripp, T.M., Savage, B.D., & Jenkins, E.B. 2001, ApJL in press, astro-ph/0003277

Valageas, P., & Silk, J. 1999, A&A, 350, 725

Yamada, M., & Fujita, Y. 2001, ApJL, 553, 14

Wu, K. K. S., Fabian, A. C., & Nulsen, P. E. J. 1999, MNRAS, 318, 889